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Comparison of Lubricant Performance in an Oscillating Spacecraft Mechanism

D. J. CARRÉ, P. D. FLEISCHAUER, C. G. KALOGERAS, and H. D. MARTEN
Chemistry and Physics Laboratory
Laboratory Operations
The Aerospace Corporation
El Segundo, CA 90245-4691

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Los Angeles Air Force Base
P.O. Box 92960
Los Angeles, CA 90009-2960

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Mark W Borden

MARK W. BORDEN, 1st Lt, USAF
MOIE Project Officer
SSD/CWDE

Jonathan M. Emmes

JONATHAN M. EMMES, Maj, USAF
MOIE Program Manager
AFSTC/WCO OL-AB

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A life test of lubricants for the R2 shaft bearings of a spacecraft oscillating scanner mechanism was performed under simulated orbital conditions. The lubricant originally used in the application, a chloroarylalkylsiloxane (CAS) oil, and a linear perfluoropolyalkylether (PFPE) oil failed in less than 2500 h of operation. A poly-alpha-olefin (PAO) oil has been running for more than 11,000 h without any indication of lubricant or system degradation. The performances of the oils are discussed in terms of the boundary lubrication conditions of the test.

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PREFACE

The authors thank Dr. R. A. Hansen of Miniature Precision Bearings for his analysis of the ball bearings after test.

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I. INTRODUCTION

The spacecraft orbital environment imposes stringent conditions on lubricants. The lubricants must perform in temperature and pressure regimes not encountered in terrestrial applications and must meet the expected system lifetimes, because there is little or no opportunity for servicing spacecraft in orbit. These constraints place severe limitations on the choice of lubricants for particular applications. As a result, ground systems and lubricant testing play an important role in lubricant selection.

We became involved in a spacecraft program in which anomalies in torque signatures were observed during testing of an oscillating scanner mechanism. One possible cause of the anomalous behavior was the ball bearings. The ball bearings originally used in the apparatus were no longer being produced. When an alternate bearing from a different supplier was substituted in testing, a failure was observed. Our initial testing was intended to assess the ball bearing performance, using the original chloroarylalkylsiloxane (CAS) oil as a lubricant, and a perfluoropoly-alkylether (PFPE) oil. After the conclusion of these tests, we felt that the bearings were adequate but that the oil originally chosen for the ball bearings was inappropriate, and that the system achieved the design life-time only through an extraordinary set of coincidences.

The currently accepted performance scenario is that the lubricant completely degrades in approximately 2000 h of operation, and the subsequent wear of the unlubricated ball bearing parts results in the complete relief of the bearing preload. In orbit, the function of the bearings is to center the shaft of the scanner, and the only load is the preload. The bearings fail to operate when the cotton-phenolic ball retainer breaks, because it must continuously change direction during the unlubricated oscillatory operation after the preload is relieved. Bearing failure has apparently occurred on orbiting spacecraft between 3 and 5 years after launch. To achieve longer system lifetimes for future missions, a more appropriate lubricant for the application needed to be chosen and tested under conditions that simulated both the system operation and the environment.

The tribological mode of system operation was such that boundary lubrication conditions prevailed throughout most or all of the oscillatory motion. Thus, the lubricant to be tested had to be capable of operation under boundary conditions and low temperatures. In addition, the lubricant had to have a low vapor pressure to avoid contamination of sensitive optics in the scanner mechanism. The test facility and lubricant testing are the subjects of this report.

II. EXPERIMENTAL

A. LUBRICANTS

Three lubricants were tested: the originally used CAS oil, a linear PFPE oil, and a poly-alpha-olefin (PAO) oil. Selected properties for the oils are given in Table 1.

Table 1. Selected Oil Properties

Property	CAS	PFPE	PAO
Viscosity, cS			
-40°C	640	2600	-
40°C	52	129	107
100°C	16	40	14.5
Viscosity index	-	350	145
Pour point (°C)	-73	-73	-55
Specific gravity	1.045	1.866	-

B. BALL BEARINGS

The R2 ball bearings were 9.53 mm in outside diameter, grade ABEC 7, and satellite flight quality. There were seven balls (each 1.58 mm diam) in each bearing. The retainer was a cotton-phenolic crown-type ball cage. The bearings used in the first test were from a different supplier than those used for the second test. However, we do not consider the differences between the bearings to be significant.

Initial torque values on bearing pairs (the bearings were used as duplex pairs in the test application) were approximately 1.5-2.0 g-cm. One pair of bearings that was used in the second test, Serial No. (S/N) 324 AB, exhibited an initial torque of ~3.5 g-cm. Although the torque was high, this pair was included in the testing because of limited availability of replacement bearings.

C. TEST FACILITY

The configuration of the test facility is shown in Fig. 1. The facility consisted of two ball bearing test cells mounted horizontally on either side of an oscillating drive mechanism so that four pairs of bearings could be tested. The drive mechanism, which was the engineering unit used by the spacecraft contractor, consisted of an inertial mass to simulate the optics and sensor array of the scanning mechanism, a brushless direct current (dc) motor, and two coiled springs that were installed opposite each other to provide a restoring force for the oscillatory motion.

Each bearing test cell consisted of two pairs of R2 bearings that were connected by a shaft to the drive motor. The drive motor was supported by two R4 ball bearings that were lubricated with the same oil as the closest test bearings. The R2 pair farthest from the motor was supported by an SR186 bearing in the housing of the test cell. The test cell configuration is shown in Fig. 2.

The ball bearing torque levels were measured using piezoelectric force transducers. The outer races of each bearing pair were clamped in a housing that was attached to the force transducer off the center of rotation to resolve the torque into a force at a known distance. The transducer arrangement is shown in Fig. 3. The transducers chosen for the application had the following characteristics: sensitivity, 4.8×10^{-13} C/N; resolution, 8.9×10^{-4} N; stiffness, 5.0×10^{4} N/mm; rise time, 15 μs; and natural frequency, 27 kHz.

The torque transducer output was read from a series of charge amplifiers by an analog-to-digital (A/D) board mounted in a personal computer using a four-channel simultaneous capture-and-hold data acquisition board. A commercially available software package was used for data manipulation and presentation. The software provided access to the data

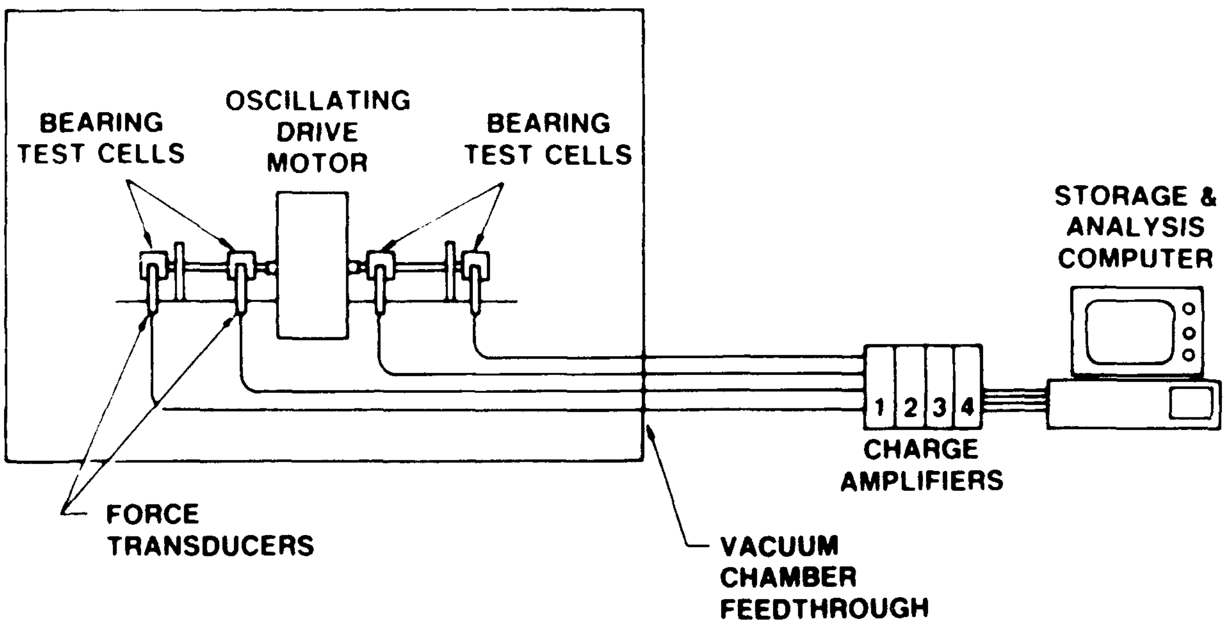


Fig. 1. Bearing Test Facility

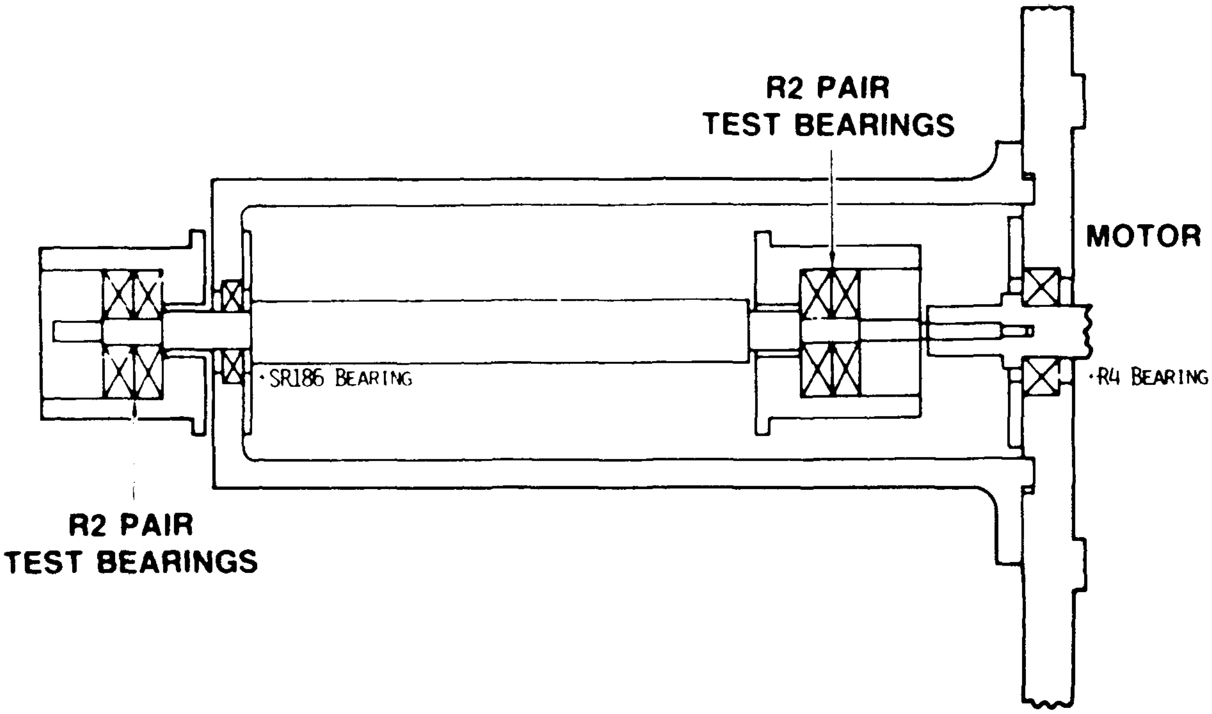


Fig. 2. Cross Section Showing the Orientation of Two Bearing Test Cells Relative to the Motor Position

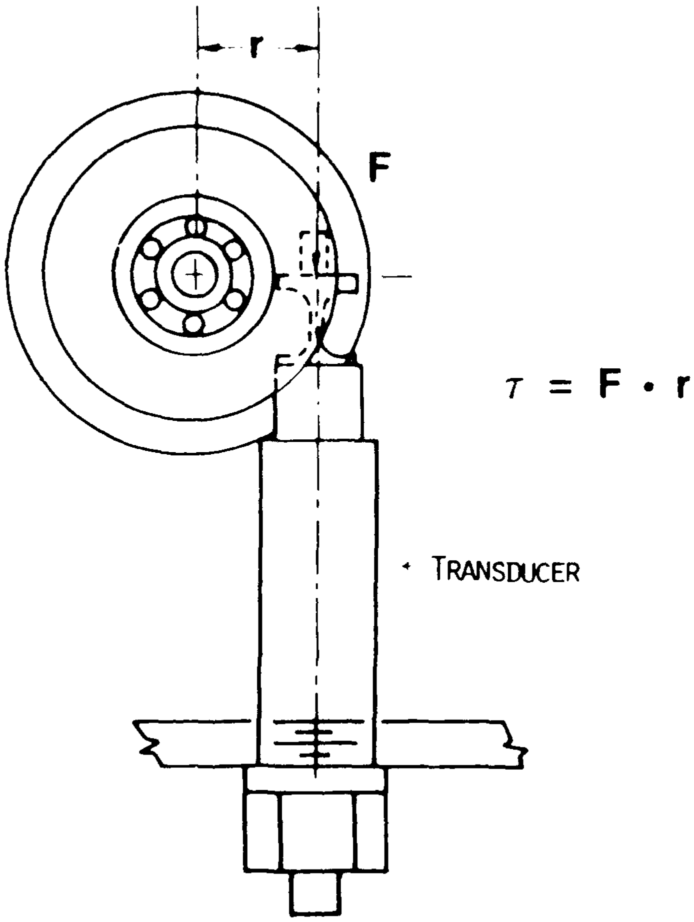


Fig. 3. End View of Bearing Test Cell

acquisition board and data analysis capability at a very high, yet very flexible, level.

The testing was intended to monitor bearing and lubricant performance under conditions simulating the real orbital environment. As a result, no enhanced loading, elevated temperatures, or other test acceleration methods were employed. The highly sensitive torque measurements were expected to indicate the onset of system degradation very early, well before the nominal 3-year lifetime.

A data compression method was used to store meaningful test data. The torque data appeared to be approximately sinusoidal, so the data were fit using Gauss-Newton curve-fitting methods, keeping only the period, amplitude, initial phase angle, and goodness-of-fit parameters. In this way, more than 200 data points, taken at a sampling rate of 50 samples/s, could be reduced to four numbers. The process of curve fitting was repeated 200 times/day, and the 800 values for each channel were saved in a file each day. In addition to the compressed data, very high resolution (4000 sample/s/channel) torque data were acquired and stored once a day. The high resolution trace of the torque waveform would include at least six full periods for each channel. These data were digitized but not fitted to the sinusoidal waveform.

The scanner simulator oscillated through an arc of ±57 deg at a frequency of ~6 Hz. The test bearings were mounted in duplex pairs with a hard preload of 13.4 ± 2.2 N. The entire test facility was housed in a vacuum chamber with test pressures of $\leq 1.3 \times 10^{-6}$ Pa. The tests were run at ambient temperature, with the temperature of each test cell monitored so that temperature increases resulting from higher torque could be observed.

In the first test, the CAS and PFPE lubricants were tested on two bearing pairs each. During the testing, malfunctions in the torque transducers in one test cell resulted in the removal of the PFPE lubricated bearings from the fixture. The test was continued with just the CAS lubricated bearings, until failure. The PFPE lubricated bearings were then returned to the fixture and tested until failure. After this test and an assessment of the results, a second test was initiated, in which a new set of four bearing pairs was lubricated with the PAO oil. In this test, two pairs of bearings were removed and analyzed at ~4300 h. Another pair was removed and examined at ~6400 h. The remaining pair is still under test and, as of 22 June 1990, has achieved over 15,000 h test time without any sign of performance degradation.

III. RESULTS AND DISCUSSION

A. TEST 1--CAS AND PFPE LUBRICANTS

The results of the CAS and PFPE tests are given in Table 2. The wear lives listed are total test times for the lubricants on the bearings. In

Table 2. Test Wear Life Data

Oil	Wear Life (h)
CAS	1500
PFPE	2350
PAO	>11,000*

*Continuing under test.

the first test, the runs were terminated because the torque traces developed significant noise. Figure 4 displays two high resolution torque traces for one of the CAS lubricated bearing pairs: one trace was taken at the beginning of testing, and one was taken at ~1500 h running time. The second trace is noisier than the first one and has a slightly reduced amplitude. (Torque traces taken for the other CAS bearing pair were similar to the traces in Fig. 4.) The testing was terminated at ~1500 h running time, and the bearings were removed from the facility and examined. Three of the four bearings had experienced complete lubricant degradation, i. e., the lubricant consisted of black solid debris. The fourth bearing showed signs of incipient lubricant degradation but appeared to be well lubricated. Figure 5 exhibits photographs of the duplex bearing pair that contained the fourth bearing. Because these bearings were mounted as a duplex pair, the only explanation we have for the differences in appearance between them is that they were unequally loaded. This unequal loading could have been the result of deflections in the shaft, of

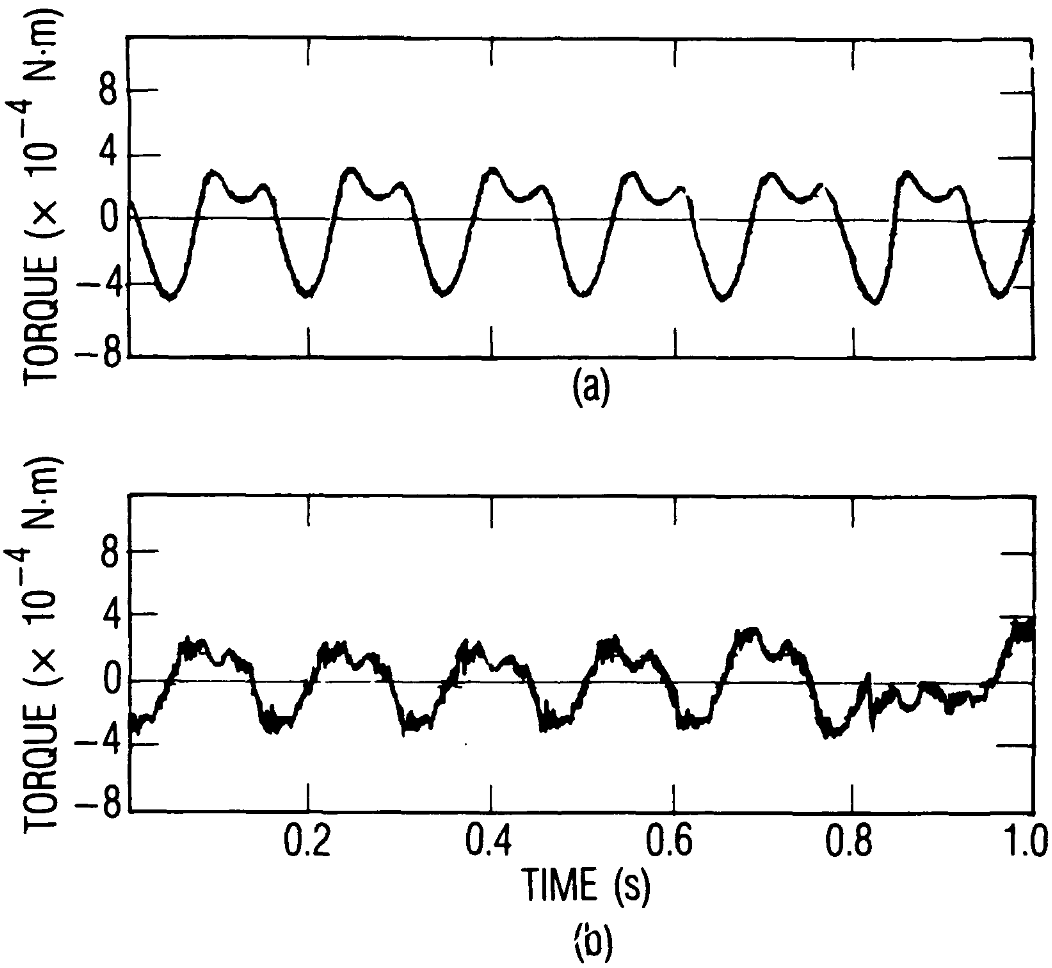
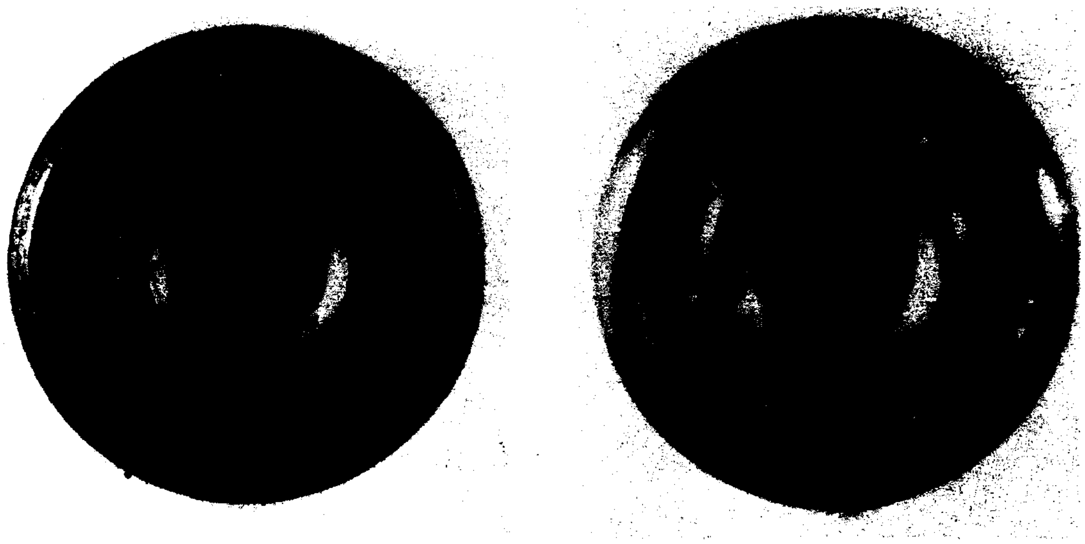


Fig. 4. High Resolution Torque Traces for CAS Oil.
(a) Initial trace; (b) trace taken at 1500 h.



G267A **G267B**

Fig. 5. Duplex Bearing Pair from CAS Oil Testing.

differences in Hertzian contact stress because the two bearings had different internal clearances, or of both situations. To elaborate on the possibility of different internal clearances, the two ball bearings could still have met the specifications but have had significantly different internal contact stress if they were at opposite extremes in their clearance parameters. Regardless of the explanation, it is obvious that bearing failure occurred because of lubricant degradation.

Figure 6 displays the high resolution torque data for one bearing pair that was lubricated with the PFPE oil. (The top trace was not taken at the beginning of the test but was taken when the PFPE test was restarted. That is why there is some noise exhibited on the trace.) The torque trace at ~2350 h running time had become very noisy, and the torque amplitude had decreased substantially. The decrease in amplitude indicates the loss of preload in the bearings. The bearings from this test were removed and inspected. As for the CAS lubricated bearings, three out of four bearings exhibited complete degradation, and the fourth revealed only signs of incipient degradation. Figure 7 exhibits photographs of the duplex bearing pair that contained this fourth bearing. The lubricant obviously failed completely on one bearing and partially on the other bearing. In past test experience, we observed that the initial degradation reaction exhibited by the fourth bearing was rapidly followed by complete degradation similar to that observed for the other bearings. In addition, because the bearings were mounted as duplex pairs, if one bearing of a pair failed, then the pair failed the testing.

Clearly, for the tribological conditions encountered by the scanner bearings, i. e., boundary conditions, the CAS and PFPE oils are woefully inadequate. PFPE oil is inadequate primarily because of the current unavailability of soluble antiwear additives and its reactivity with iron

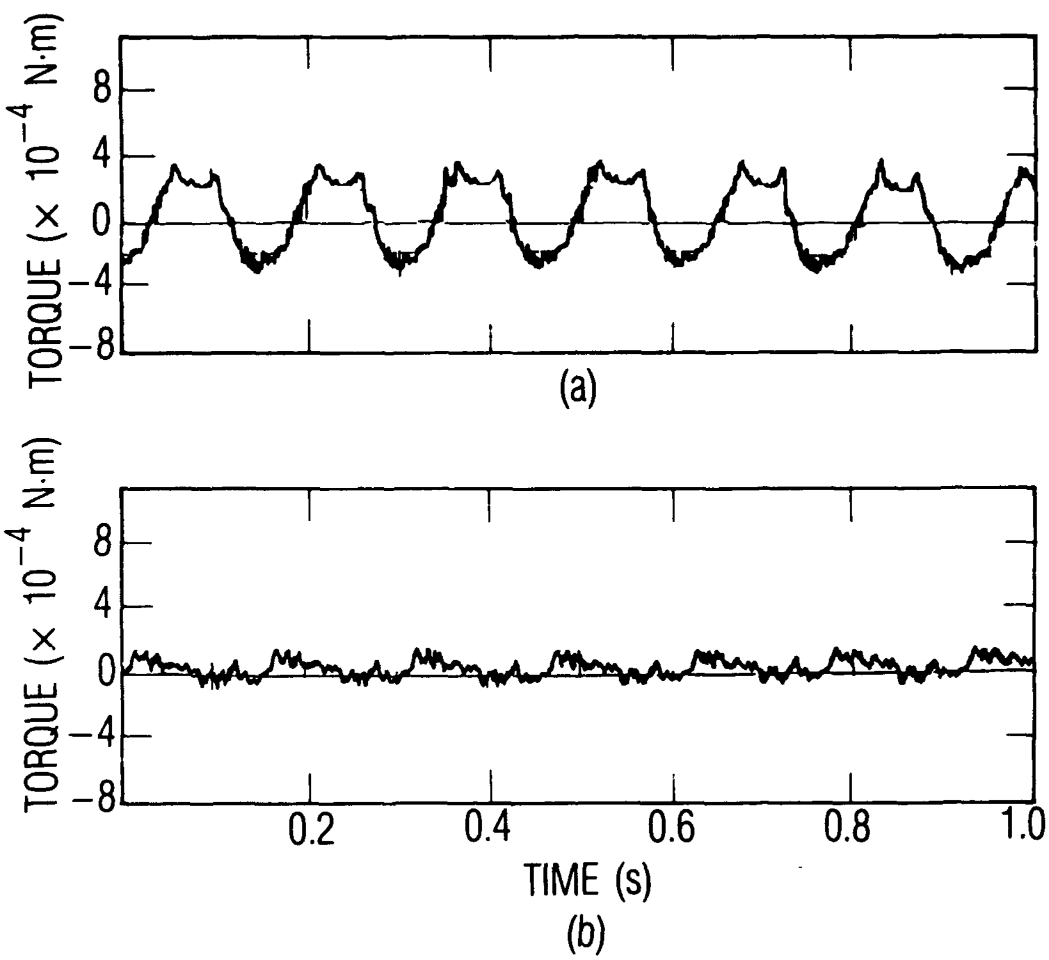
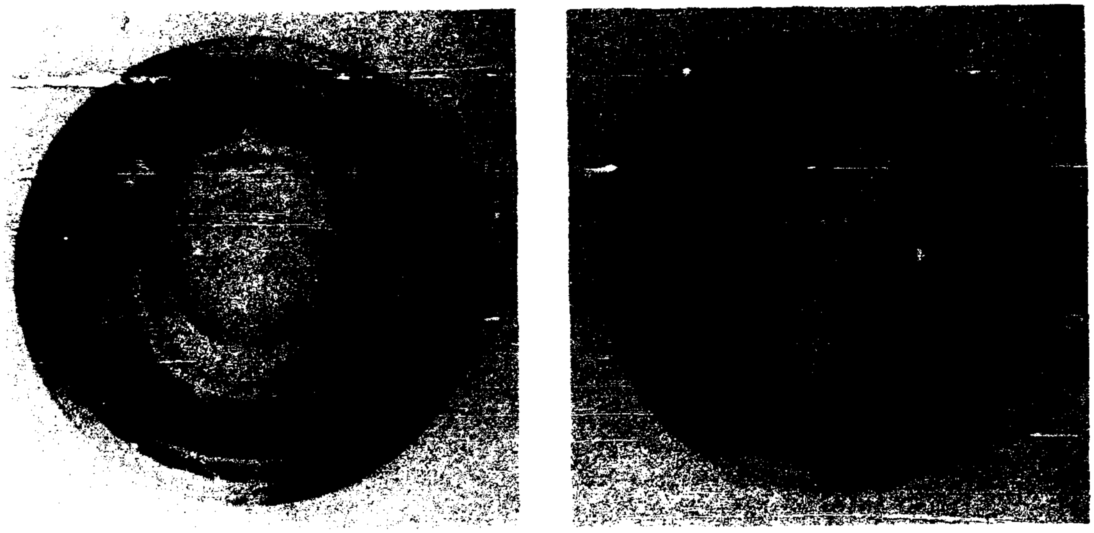


Fig. 6. High Resolution Torque Traces for PFPE Oil.
(a) Trace taken at restart, at 360 h running time;
(b) trace taken at 2350 h.



G243A **G243B**

Fig. 7. Duplex Bearing Pair from PFPE Oil Testing

surfaces at the high contact temperatures.[1-3] The CAS oil is inadequate because it does not contain antiwear additives or react favorably with the metal surfaces to form chemical species that afford boundary protection. Some chemical reaction has occurred because the oil has degraded significantly, but this reaction has not resulted in surface protection.

Because of the problems with the PFPE and CAS oils, a different lubricant was chosen for testing: PAO oil. This oil was selected because it could be formulated with an antiwear additive, in this case, tricresylphosphate (TCP); had a low vapor pressure (a programmatic constraint); and had an acceptable viscosity and viscosity index for the application.

B. TEST 2--PAO LUBRICANT

The results for the PAO test are given in Table 2. Figure 8 exhibits the torque traces for one of the PAO lubricated ball bearings initially and after ~4300 h of testing. Clearly, there is little difference between the traces from the beginning of testing and after 4300 h. Figure 9 reveals photographs of the bearings removed at 4300 h. Lubricant had migrated from one bearing to another in each bearing pair, but there was no sign of lubricant degradation in any of the ball bearings. The two bearing pairs were sent to the supplier to check the condition of the surfaces, and the roundness, cross-curvature, and preload parameters. The preloads were essentially unchanged, within the operator error range associated with the preload measurement technique. One bearing-pair preload changed from 12.7

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[1]D. J. Carre, "Perfluoropolyalkylether Oil Degradation: Inference of FeF_3 Formation on Steel Surfaces under Boundary Conditions," ASLE Trans., Vol. 29, pp. 121-125.

[2]D. J. Carre, "The Performance of Perfluoropolyalkylether Oils under Boundary Conditions," Tribology Trans., Vol. 31, pp. 437-441.

[3]D. J. Carre, and Markowitz, J. A., "The Reaction of Perfluoropolyalkylether Oil with FeF_3, AlF_3, and $AlCl_3$ at Elevated Temperatures," ASLE Trans., Vol. 28, pp. 40-46.

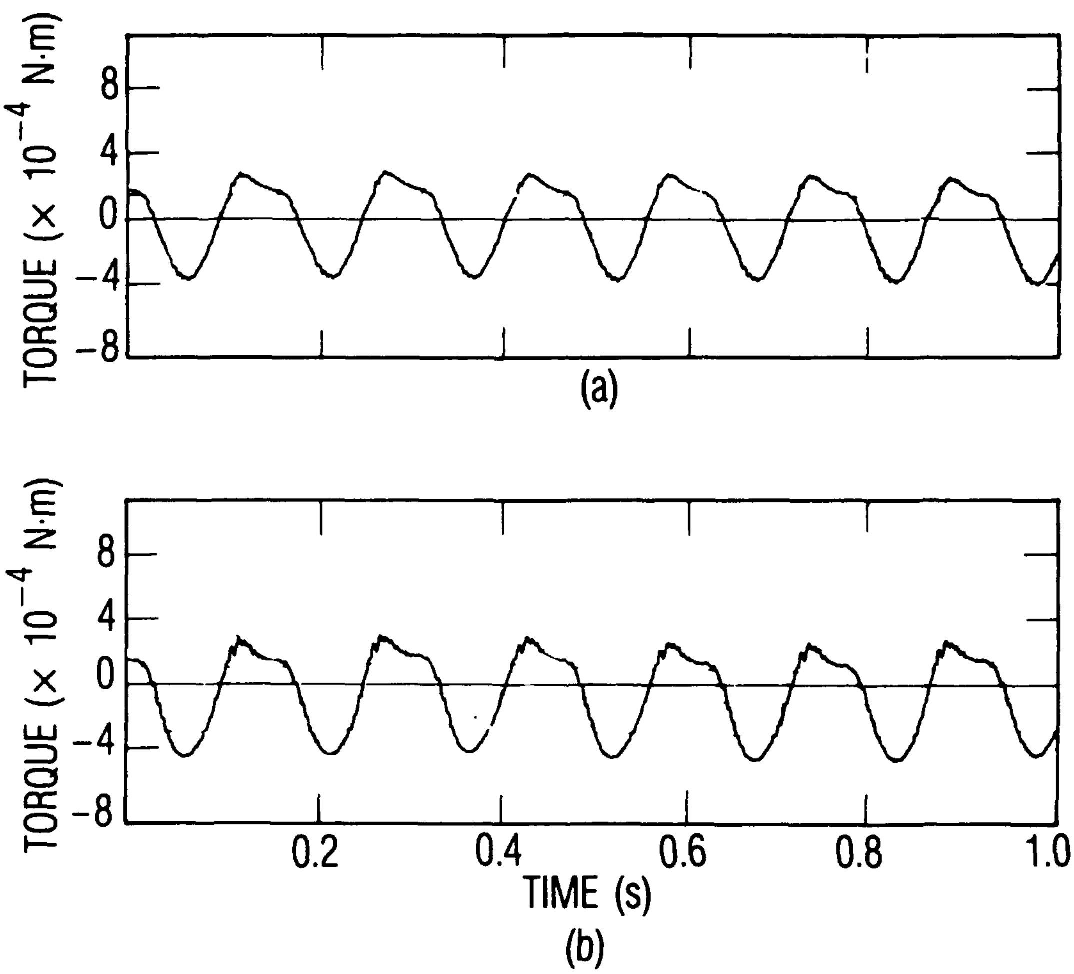


Fig. 8. High Resolution Torque Traces for PAO Oil.
(a) Initial trace; (b) trace taken at 4300 h.

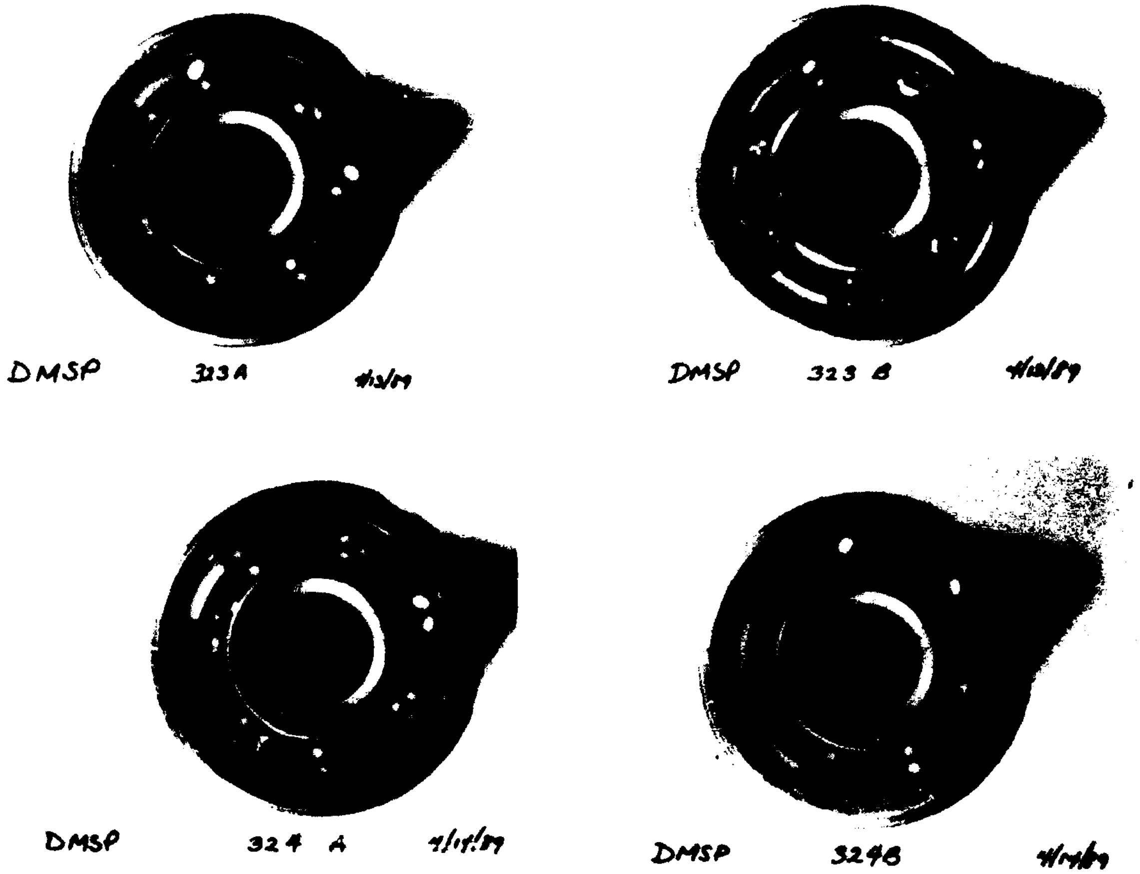


Fig. 9. Duplex Bearing Pairs from PAO Oil Testing; 4300 h Running Time.

to 8.9 N, whereas the other bearing-pair preload remained constant at 15.1 N. The surfaces in the ball track were slightly worn, more so than would be expected for conventional instrument bearings. However, because these bearings were operated under boundary conditions during test (as in the real application) and not under the elastohydrodynamic conditions generally associated with conventional instrument bearing operation, the wear was not considered to be especially significant. The data indicated that one ball in the S/N 324 AB bearing pair was oversized. This ball was larger than the other balls in the pair by 0.01 mm (and had a nominal diameter of 1.58 mm)--a large amount. This difference in ball size may account for the high initial torque that was measured for this bearing pair.

Figure 10 displays the high resolution torque traces for the bearings that were removed at ~6400 h. (The torque amplitude on the 6400 h trace is greater than that on the initial trace. This increase is not the result of a torque increase during running, but rather, is the result of adjustments made in the torque transducers when the other two bearing pairs were removed at 4300 h.) As with the traces in Fig. 8, there were no significant increases in noise on these traces. A unique anomalous event was observed with this bearing pair. Photographs of the bearings are exhibited in Fig. 11. As shown in the photographs, a very large metal piece from the surface of one ball apparently had become detached and found its way, intact, to the cage of the other bearing in the pair, without getting into the ball track area. We discussed this observation with several individuals from the ball bearing suppliers. Only once, in 25 years, had one of them observed a similar phenomenon. We concluded that the "event" was the result of a metallurgical defect below the surface of the ball that managed to get through quality control. It is amazing that there were no signs of the anomaly in the torque traces. Unless the anomaly occurred right at the end of testing, some sign of it would have been expected in the torque data.

The last remaining bearing pair for the PAO lubricated testing was examined at ~6400 h. The bearings were well lubricated and showed no signs of lubricant degradation. The bearing pair was placed back in the test

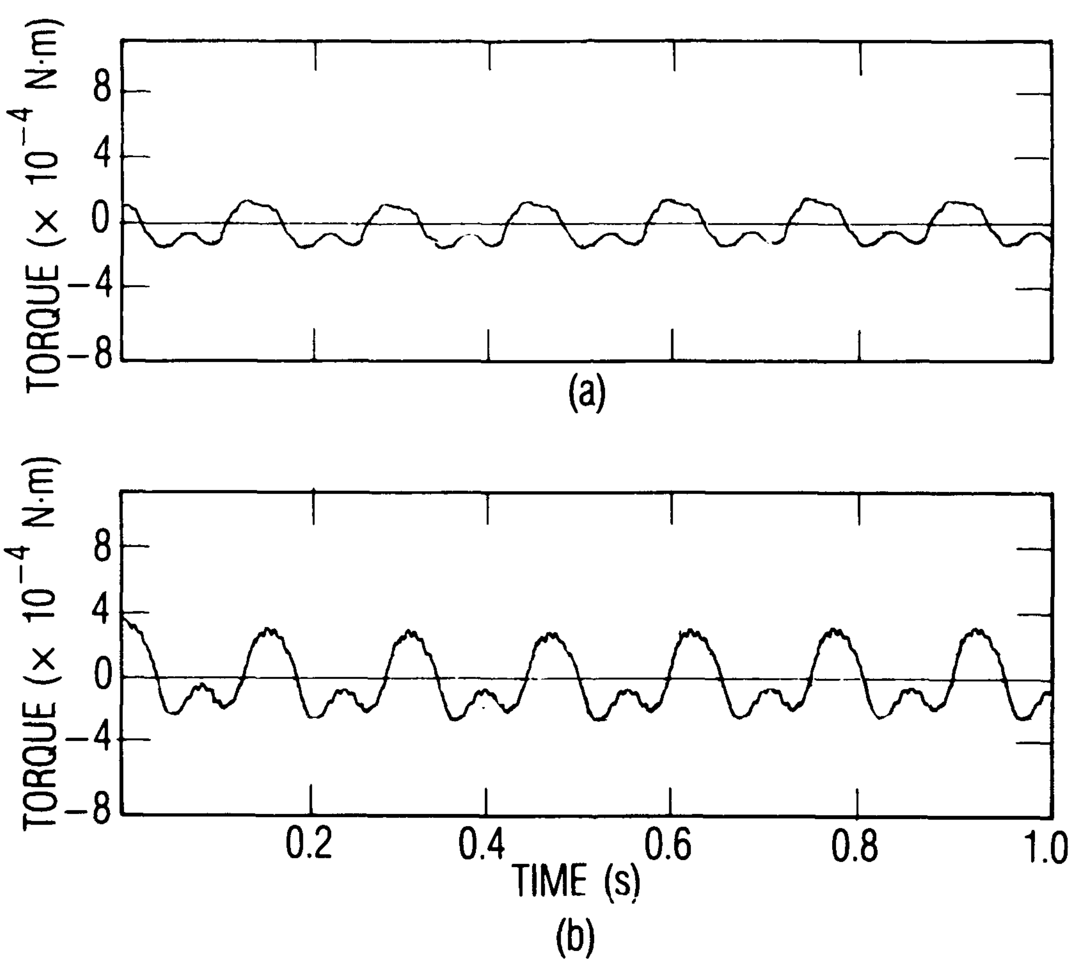
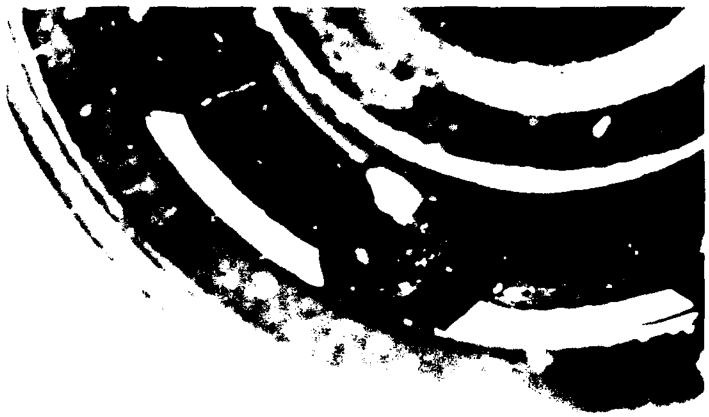


Fig. 10. High Resolution Torque Traces for PAO Oil.
(a) Initial trace; (b) trace taken at 6400 h.



325B

325A

Fig. 11. Duplex Bearing Pair from PAO Oil Testing; 6400 h Running Time.

fixture, and the test was restarted. As of 22 June 1990, this bearing pair had logged more than 15,000 h of test time without any sign of system degradation. The testing of this bearing pair is continuing.

IV. CONCLUSIONS

The results of the testing of several lubricants under simulated orbital conditions and in a satellite scanning mechanism have led to the following conclusions.

1. The CAS and PFPE lubricants are both inadequate for use in orbiting satellite scanner mechanisms, because these oils perform poorly under boundary lubrication conditions. They both exhibited complete lubricant degradation in less than 2500 h under the test conditions.

2. The PAO lubricant has demonstrated superior performance in our testing. One bearing pair has logged more than 15,000 h test time and is still running, without exhibiting any signs of lubricant or system degradation. The PAO oil was formulated with TCP antiwear additive, which contributes to its excellent boundary lubrication performance.

LABORATORY OPERATIONS

The Aerospace Corporation functions as an "architect-engineer" for national security projects, specializing in advanced military space systems. Providing research support, the corporation's Laboratory Operations conducts experimental and theoretical investigations that focus on the application of scientific and technical advances to such systems. Vital to the success of these investigations is the technical staff's wide-ranging expertise and its ability to stay current with new developments. This expertise is enhanced by a research program aimed at dealing with the many problems associated with rapidly evolving space systems. Contributing their capabilities to the research effort are these individual laboratories:

Aerophysics Laboratory: Launch vehicle and reentry fluid mechanics, heat transfer and flight dynamics; chemical and electric propulsion, propellant chemistry, chemical dynamics, environmental chemistry, trace detection; spacecraft structural mechanics, contamination, thermal and structural control; high temperature thermomechanics, gas kinetics and radiation; cw and pulsed chemical and excimer laser development, including chemical kinetics, spectroscopy, optical resonators, beam control, atmospheric propagation, laser effects and countermeasures.

Chemistry and Physics Laboratory: Atmospheric chemical reactions, atmospheric optics, light scattering, state-specific chemical reactions and radiative signatures of missile plumes, sensor out-of-field-of-view rejection, applied laser spectroscopy, laser chemistry, laser optoelectronics, solar cell physics, battery electrochemistry, space vacuum and radiation effects on materials, lubrication and surface phenomena, thermionic emission, photosensitive materials and detectors, atomic frequency standards, and environmental chemistry.

Electronics Research Laboratory: Microelectronics, solid-state device physics, compound semiconductors, radiation hardening; electro-optics, quantum electronics, solid-state lasers, optical propagation and communications; microwave semiconductor devices, microwave/millimeter wave measurements, diagnostics and radiometry, microwave/millimeter wave thermionic devices; atomic time and frequency standards; antennas, rf systems, electromagnetic propagation phenomena, space communication systems.

Materials Sciences Laboratory: Development of new materials: metals, alloys, ceramics, polymers and their composites, and new forms of carbon; nondestructive evaluation, component failure analysis and reliability; fracture mechanics and stress corrosion; analysis and evaluation of materials at cryogenic and elevated temperatures as well as in space and enemy-induced environments.

Space Sciences Laboratory: Magnetospheric, auroral and cosmic ray physics, wave-particle interactions, magnetospheric plasma waves; atmospheric and ionospheric physics, density and composition of the upper atmosphere, remote sensing using atmospheric radiation; solar physics, infrared astronomy, infrared signature analysis; effects of solar activity, magnetic storms and nuclear explosions on the earth's atmosphere, ionosphere and magnetosphere; effects of electromagnetic and particulate radiations on space systems; space instrumentation.